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Water Penetration of Cladding Components – An Overview of the Vulnerability of Sealed Joints to Water Penetration

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ABSTRACT

The deterioration of jointing compounds used to seal building joints has been thoroughly investigated whereas that of relating the consequences of failure of jointing products, whilst generally understood, has not been studied in depth, in particular in respect to loss in watertightness. Jointing products age due to natural weathering effects that, in time, lead to deficiencies in the product and, in turn, lead to the local failure of the jointing system. Deficiencies may also occur from design faults or improper installation. Water penetration at deficiencies may lead to a number of different deteriorating effects on the building fabric that may induce failure of other envelope components or the loss in adhesion of the sealant. Joints are also subjected to significant wind-driven rain loads in particular atop multi-storey buildings located along an exposed coastline. To what extent are joints vulnerable to water leakage when subjected to a rain event, such as a typhoon, as might be experienced in Japan, or a hurricane as in North America? The question of fault tolerance in jointing systems has not yet been broadly explored. An overview is provided on the nature of water entry at sealed joints of cladding systems and information is also presented on a study related to water penetration at joints. Small deficiencies in jointing systems may lead to significant water entry when such joints are subjected to severe wind-driven rain loads.

KEYWORDS: FAULT TOLERANCE, JOINT DEFICIENCIES, SEALANT FAILURE, WATERTIGHTNESS, WATER PENETRATION, TESTING

RÉSUMÉ

La détérioration des matériaux de colmatage de joints de construction a déjà été étudiée de manière approfondie alors que la détérioration dans le contexte des conséquences de la défaillance de ces matériaux, bien qu'elle soit généralement comprise, n'a pas été étudiée en profondeur, en particulier en ce qui concerne la perte d'étanchéité à l'eau. Les matériaux de colmatage de joints vieillissent à cause des effets naturels d'exposition aux intempéries, qui, à long terme, entraînent des déficiences dans le matériau, et par le fait même, la défaillance du système de joints. Les défauts de conception ou une mauvaise installation peuvent également être à l'origine des déficiences. La pénétration de l'eau aux endroits des déficiences peut conduire à de divers types de détérioration de l'enveloppe du bâtiment, qui peuvent engendrer la défaillance d'autres éléments de l'enveloppe ou, par ailleurs, la perte d'adhérence du mastic d'étanchéité. Les joints sont également soumis à d'importantes surcharges de pluie battante, en particulier dans les zones les plus élevées des bâtiments de plusieurs étages situés le long d'un littoral exposé. Dans quelle mesure les joints sont-ils vulnérables à de l'infiltration d'eau lorsqu'ils sont soumis à une averse importante, tel qu'il se produit durant un typhon au Japon, ou un ouragan en Amérique du Nord? La question de la tolérance aux déficiences des systèmes de joints n'a pas encore été largement étudiée. Un aperçu est fourni sur la nature de l'infiltration d'eau aux joints des systèmes de revêtement extérieurs et de l'information est également présentée sur une étude relative à la pénétration d'eau aux joints. Des petites déficiences dans les systèmes de joints peuvent conduire à une importante infiltration d'eau quand ces joints sont soumis à des surcharges de pluie battante élevées.

MOTS CLEFS: TOLÉRANCE AUX DÉFAUTS, DÉFICIENCES DES JOINTS, MASTIC D'ÉTANCHÉITÉ, ÉTANCHÉITÉ A L'EAU, PÉNÉTRATION D'EAU, ESSAIS

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INTRODUCTION

Considerable work has focused on the deterioration of jointing compounds used to seal building joints; less emphasis has been placed on understanding the consequences of seal failure, in particular in respect to loss in watertightness. Loss in watertightness at joints is of some importance since water entry may lead to a number of different deteriorating effects on the building fabric that in turn may induce failure of other envelope components or bring about loss in adhesion of the sealant.

For example, water penetration at joints may bring about:

- Excessive moisture uptake by porous building components adjacent to the joint thus in a cold climate, perhaps increasing the risk to freeze-thaw action on masonry, concrete or mortar components;
- Increased time of wetness on metal elements thereby increasing their susceptibility to corrosion;
- Wetting of façade components necessary to ensure adequate thermal resistance that could lead to a reduction in the thermal performance of the wall assembly.

Water penetration may not only accumulate in the building fabric but across it. Hence, water may penetrate the interior and cause damage to the interior wall or floor finish and related components.

Jointing products placed on the exterior face of the wall assembly are subjected to direct exposure to the different climatic elements, some of which induce aging in the sealant that in time may lead to deficiencies. For example, joints undergo cyclic movement on a daily basis that is superimposed on an annual cycle of movement [1] whilst being exposed to the effects of solar radiation and wind driven rain. Hence those products that have direct exposure to sunlight are both heat aged and exposed to UV radiation that in some products may cause additional deterioration. In a cold climate, such as is found in Canada and northerly parts of Japan (e.g. Hokkaido), movement occurring during cold months subjects sealant products to cold temperature deformation. Some products may increase in modulus in colder temperatures and are thus less able to accommodate movement at these lower temperatures making them more susceptible to forming deficiencies in these conditions. Apart from the action of natural weathering on jointing products, it is well understood in the waterproofing and sealant industry that deficiencies in joints may also come about from both design faults and improper installation [2].

Joints are also subjected to significant wind-driven rain loads in particular atop multi-storey buildings located along an exposed coastline. Given that the maintenance of jointing systems is an aspect in the maintenance of the building or facade that is often overlooked, is there any cause for concern on the part of a building manager in respect to watertightness of the facade? To what extent are joints vulnerable to water leakage when subjected to an average rain event, or an event such as a tropical storm as might be experienced in Japan or North America? Are there portions of the building that are more vulnerable than others given the expected degree of exposure of the jointing products to the effects of natural weathering and the location and height of the building and its exposure to wind-driven rains? The question of fault tolerance in jointing systems has not yet been fully explored at the level of detail that would permit the further development of a maintenance program for building facades, as proposed by Kyle in [3]. Previous work on the water entry at failed joints of penetrations in low-rise wood frame construction was reported by Lacasse et al. [4]. However, the results from this work have in part focused on rates of water entry at a specific type and size of deficiency that would be typical of a wood frame wall and not a jointing system located in, e.g., a precast concrete wall. As well, the results have not been considered from the point of view of the maintenance management of building facades.

The principles of rain penetration control [5, 6] are well understood and it is acknowledged that a jointing system may be comprised of a one- or two-stage seal for which the air and watertightness function is taken up by a single component in the one-stage joint whereas for the two-stage joint, these functions are separated by an air cavity, the cavity helping equalize pressure differences across the exterior joint [7, 8, 9]. Given that these functions are separated, the interior component of the two-stage joint, in principle, provides for airtightness, the exterior joint the watertightness. Thus a deficiency at the outer joint does not necessarily produce water entry through the jointing system given the level of redundancy of the two-stage joint. Hence, the comportment of two-stage joints are superior to that of single stage joints although defects of the interior seal may very well lead to water entry [10]. Such jointing systems would typically be specified for panelised buildings constructed in North America and Japan. However, whether one-or two stage, the exterior seal will in time deteriorate and water will enter the jointing system. The question remains, how much water entry given the joint type (one or two-stage), configuration (width, depth and orientation), displacement, size of deficiency and the wind-driven rain loads acting of the joint?

This paper provides an overview on the nature of deterioration of jointing products and implications in respect to the location of deficiencies on buildings as might help better understand the inspection and maintenance process. This is juxtaposed to knowledge of the range of wind-driven rain loads to which a building may be exposed and the difference in rain loads over the height of the building. Based on this information the vulnerability of deficient joints to rain loads is discussed from which the fault tolerance of joints is more fully described. Finally, information is given on recent laboratory studies undertaken to assess the watertightness of model joints and the susceptibility of deficient joints to water entry when subjected to extreme climate loads.

THE NATURE OF DETERIORATION OF SEALANT JOINTING PRODUCTS

Nature of deterioration of building joint sealants

All jointing products deteriorate over time due to the effects of natural weathering on the products brought about by the specific climatic conditions that prevail at the building location. The microclimate at the façade in relation to the climate of the building location is less well known but certain weathering parameters can be estimated based on average climate conditions. For example, the surface temperature can readily be determined based on knowledge of the colour of the sealant and the orientation of the building façade [11]. The degree of movement of the joint can be estimated from knowledge of the joint width, the physical characteristics of the cladding components adjacent to the joint, and the expected maximum and minimum temperatures that occur on the cladding over a year [12].

Depending on the response of the jointing product, that is, the degree of movement to which the product is subjected over a daily and yearly cycle in relation to its' movement capability, some will deteriorate more quickly than others, the deterioration manifesting itself as either adhesive or cohesion in nature. By adhesive deficiencies one refers to joints in which the product has lost adhesion to the substrate to which it was applied whereas in the case of cohesive deficiencies, these would be evident by rupture in the bulk of the product. Cohesive failures are much less common today given the development of high performance products. However, such failures nonetheless occur, e.g., when two-component jointing products formulated on-site are incompletely mixed. The lack of adequate mixing of such products may prevent them from curing sufficiently to develop the necessary elasticity and resilience, typical in rubbery compounds, and necessary to adequately perform as a building joint seal. Nonetheless, the primary factors affecting the ageing of sealant products are movement due to climate effects and weathering from exposure to sunlight [13, 14].

In the northern hemisphere the degree of exposure to solar radiation of products in south-facing joints is greater than that of the other cardinal directions; the same can be stated for north facing building joints exposed in the southern hemisphere. Hence in North America, south-facing products would tend to have a greater degree of exposure to heat ageing and UV radiation, thus rendering this group of joints more susceptible to deterioration than those facing other directions. Likewise, the degree of movement attained by joints on a south facing building is likely to be greater as compared to, for example, the north face as the maximum exterior surface temperature will be greater thereby subjecting the jointing product to a comparatively greater overall movement over a year in relation to its' movement capability.

All of such considerations regarding movement are typically taken into consideration in the design of joints and the selection of products appropriate for the expected average yearly movement at the joint [12].

Deficiencies in building joint systems – incidence of defects

The overall length of sealant placed in a typically pre-cast concrete facade building may be considerably longer than 1 km; e.g. consider the overall length of sealant placed in a square four-sided 12-storey building. The facade may be comprised of similar exterior pre-cast concrete panel height and widths of, say, a set of six 3.5 m panels across the facade. On each face there would be ca. 21 m of horizontal sealant joint at each storey height or 84 m for the perimeter of the building or a total of ca. 1008 m of horizontal joint for the building. Similarly for the vertical joints, this would give ca. 1008 m and combining this value with that previously estimated for horizontal joints yields a total of 2.1 km for this building. What are the risks to improper installation of ca. 2 km of jointing product over the course of the installation process given that the process may take several months to complete in different weather conditions and using uncertain expertise? How many defects would be revealed following a maintenance inspection for a given length of vertical or horizontal sealant?

Few comprehensive surveys have been published on the incidence of failure in building joints; there is literature that is of some value, notably that from survey work carried out in the UK [15], the results of which are reportedly [16] emulated by a similar work in Japan [17]. The highlights of the survey conducted in 1990 in the UK indicated that 55% of joints failed within less than 10 years, and only 15% lasted more than 20 years.

In North America, little has been published on this topic although there is information on individual buildings, specifically that published by Huff [18] who provided examples of two surveys, one of which was carried out on a newly constructed 11-storey building and the other, on a twin 18-storey condominium in Long Beach, California. It the latter case, a 5.6% failure rate was detected in the EIFS cladding joints based on 1%, 5%, and 10% sampling rates. Huff [18] determined from this that the failure rate remained constant irrespective of the sample size.

The former example [18] of the 11-storey building had a total of ca. 35,000 feet of jointing product installed. The survey was conducted on 2 of 24 grid locations representing an 8.3% sampling rate. From this study, 14 adhesive failures were detected on one grid section, and 20 on the other, yielding an average of 17 failures per grid section. Based on this information an estimate of the number of failures in adhesion of the entire building was 408 whereas, following a survey of the entire building 427 adhesive failures were uncovered (i.e., a 0.2% failure rate). The author noted that although the failure rate appears small, there are nonetheless 427 failure locations that represents, based on an average length of failure of 50 mm (2-in.), approximately 21.6-m (71-ft.) of product that has failed and through which water can enter.

An investigation of defects and complaints of execution of constructed works in Japan was reported by the Building Construction Society of Japan, results for which are summarized in Table 1 [19]. The results indicated that 65% related directly to water leakage, of which 44% could be attributed to water leakage of the wall system and of this proportion, 32% of the defects were due to leakage at the exterior of the wall. Based on the results of this study, it is evident that a considerable proportion of defects accrue from water leakage alone. Thus understanding the nature of wind-driven rain is important when assessing the loads to which the building envelope is subjected. Additionally, considering the relatively high portion of defects attributable to jointing systems suggests that attention be placed not only on the nature of failure at joints but also, the consequences of failure.

In respect to the nature of failure at joints, the Building Construction Society of Japan reports on the different types of failure of jointing products, as summarized in FIGURE 1 [20]. The greatest proportion of failures can be attributed to failure due to adhesion (56%), whereas, the proportion of failures in cohesion is reported as 24% [20].

TABLE 1: INVESTIGATION OF DEFECTS AND COMPLAINTS OF BUILDING WORK IN JAPAN [19]

Description of defect	%
Water leakage at external wall	32
Water leakage at roof	21
Other sources of water leakage	21
Water leakage at cracks in walls	12
Delamination of interior & external wall	6
Settlement problem	5
Condensation	3

This suggests that when attempting to determine the significance of jointing product failures on the watertightness of joints, defects such as those that accrue due to adhesion failure should first be investigated as these are the more likely to occur in building joints.

In general then, deficiencies in building façade joints are inherent in any façade jointing system even those for which proper installation procedures have been conscientiously followed. These deficiencies would typically be adhesive in nature and could lead to leakage across the wall joint.

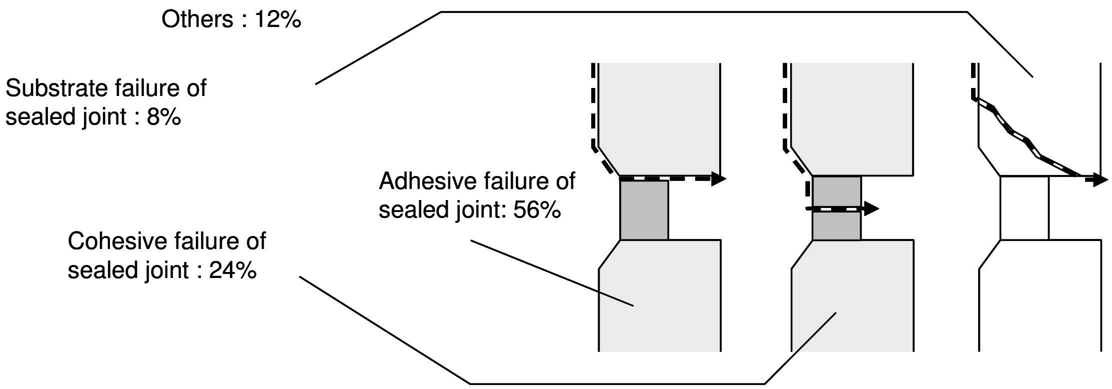

FIGURE 1: CAUSE OF FAILURE OF SEALED JOINT IN JAPAN [20]

However, given openings exist along joints, water leakage evidently can only occur if water is present at the opening and if there are forces driving water through these deficiencies. The presence of water on the façade is in part a function of the climate loads, specifically, the intensity of wind driven rain, that varies, not only in relation to the basic climate parameters of wind speed and rainfall intensity, but also in respect to the height and width of the building, and orientation of the building to the prevailing direction of the driving rain. Some basic information relating to characteristic of wind speed and rainfall intensity during key climate events is given such that these can be related to test loads used in assessing wall and cladding weathertightness performance.

THE FAULT TOLERANCE OF JOINTS - ASSESSING THE VULNERABILITY OF JOINTS TO CLIMATE LOADS

The fault tolerance of joints can readily be determined on knowing: (i) the climate loads to which joints are subjected; (ii) the type, size and distribution of deficiencies along either vertical or horizontal joints on the facade, as encountered in the field, and; (iii) the presence of water flowing over or occluding any openings at the deficiencies. In the context of assessing the weathertightness of joints, the criteria from which a fault may arise is simply the occurrence of a natural weather event that causes the passage of air or water through the joint. The question then arises as to what minimum level of passage will bring about undesirable effects on components of the building envelope susceptible to air infiltration or water uptake.

This can only be determined if a measure of the response of a deficient joint is known in relation to the load acting on it. That is, what is the expected amount of water penetration across a deficient joint given specific wind-driven rain loads acting on a joint having a deficiency of known type and size? Some information that relates to this basic load-response model is provided in a subsequent section.

The issue of the presence of openings and their distribution across the façade has to a limited extent been dealt with in previous section however little is in fact known of, for example, the likely occurrence of deficiencies in horizontal as compared to vertical joints, of deficiencies in wide as opposed to narrow joints, or the variation in occurrence of deficiencies at the intersection of joints in preference to the end points of joints.

The presence of water at a deficiency is directly related to the rate of deposition of rain on the building façade but is also a function of the cladding material itself. When rain is deposited on the facade of a non-porous, non-absorptive surface, the raindrops will tend to coalesce and may form a film or stream of water that thereafter migrates downwards across the façade due to gravity. Whereas a facade having a porous material, and subjected to similar rainfall intensity, will necessarily sorb water until the exposed surface is saturated where after a film may form and water then migrates downward.

The difference between these two scenarios is that water films are less likely to form on porous facades during the initial wetting period of a rain event given that most of the rainfall is absorbed into the façade. The remaining portion of rainfall deposited on the wall in the form of raindrops rebounds from the wall and finds its way further downward. The amount of time required to attain surface saturation of the porous cladding is dependent on the sorptivity of the material and indeed the rate of absorption of water from the surface and the rainfall intensity. For example Hall [21] projects times to surface saturation of a porous material (sorptivity = 0.077 mm-min$^{-0.5}$) of ca. 26, 3 and 0.5 minutes for water deposition rates of 0.012, 0.036, 0.084 L/min-m^2 respectively.

For non-sorptive facade surfaces, water naturally forms streams and rivulets along its downward path across the facade, finding features along which to flow. For example, vertical features such as vertical joints on the facade would tend to promote the channelling of water against or within this feature. Small openings or cracks along these vertical joints could readily be occluded by the film or stream of water and thus provide a source of water entry to the interior. Hence vertical joints may be a location along which water may stream and deficiencies along its length may be subjected to significant migrating water and wind loads. Horizontal features would necessarily impede the downward flow of water but these may, depending on the geometry of the features, retard flow sufficiently for it to pool and enter openings present at the location of water accumulation. Thus non-sorptive facade surfaces may be vulnerable to water entry at features where water can accumulate and pool as, for example, at small openings at corners of windows or jointing gaskets.

Climate loads

Wind driven rain is necessarily characterized by two basic climate parameters: wind or wind speed, and rainfall intensity, the latter parameter typically referred to as the rainfall rate and reported in mm/h (in./h). Extreme wind driven rain events are usually associated with thunderstorm activity and tropical cyclonic events such as tropical storms, typhoons (in the Western Pacific) and hurricanes (in the Eastern Atlantic). What range of wind speeds would be associated with a tropical storm, hurricane or typhoon? Table 2 provides the range of wind speeds and related velocity pressures in relation to different categories of tropical cyclonic events.

The values provided in Table 2 are those that occur at a height of 10-m, the height at which meteorological data are collected. Thus, these would suffice for estimating the wind loads for a residential building of three stories or less.

TABLE 2: CHARACTERISTIC WIND SPEEDS AND RELATED VELOCITY PRESSURES FOR DIFFERENT CATEGORIES OF TROPICAL CYCLONIC EVENTS

Category	Wind speed (km/h)	Velocity pressure* (Pa)
WEAK TROPICAL STORM		
Speeds / velocity pressures	43 - 68	92 - 231
Gust speeds / pressures	65 - 104	211 - 540
SEVERE TROPICAL STORM		
Speeds / velocity pressures	68 - 104	231 - 540
Gust speeds / pressures	105 - 150	550 - 1122
Category 1 HURRICANE / MINIMAL TYPHOON		
Speeds / velocity pressures	104 - 131	540- 856
Gust speeds / pressures	151 - 194	1137 - 1877

* P_υ (Pa) = ½ $\rho\upsilon^2$; ρ_{air} (0°C) = 1.293 kgm^{-3}; υ (ms^{-1})

Wind loads atop buildings of greater height can be estimated by using a power law relationship† for wind velocity profiles [22]. These loads can also be adjusted according to the exposure of the building, as buildings exposed in an open flat terrain or along coastal belts would have greater loads as compared to those located in an urban or suburban setting.

For example, using this relationship, and assuming wind velocities at 10 m consistent with the range of speeds associated for a severe tropical storm (i.e. 68 – 104 km/h), information on velocity pressures at different building heights for different exposure categories can be estimated as given in Table 3. The information is important because it shows that the pressures are not linearly proportional to the height but vary exponentially in height, thus the severity of the wind can be significantly more important atop tall buildings as compared to low-rise structures. This may be self-evident however, it bears directly on the risk to water entry through small openings in exposed joints of tall buildings as the risk to entry is itself proportional to the pressure difference across the joint.

TABLE 3: ESTIMATE OF VELOCITY PRESSURES AT DIFFERENT BUILDING HEIGHTS ASSOCIATED WITH SEVERE TROPICAL STORMS

Height (m)	Storey*	Velocity pressure (Pa)	
		Open, flat, unobstructed	Urban, suburban
10	3	231 – 540	115 – 270
30	10	316 – 738	177 – 415
75	25	410 – 959	280 – 656
150	50	500 – 1170	396 – 927

*Estimate assuming a 3-m storey height

Rainfall intensity during storms

An example of the amount of rainfall that can occur during a typhoon in provided in FIGURE 2 [23] which shows the temporal variation in rainfall intensity for an occurance of two typhoons in Taiwan in 1996. Taiwan receives an annual rainfall of 2,500 mm of which 80 % of the annual rainfall occurs from May to October, the greater proportion during typhoons. Rainfall intensity during some typhoons may exceed 100 mm/h and 1,000 mm over a 24 h period with the recorded maximum one-hour and 24-hour rainfall before 1996 being 300 mm and 1,672 mm, respectively [23]. As can be seen in FIGURE 2 the recorded 24-hour rainfall was broken by the heavy rain accompanying the typhoon and reached 1,994 mm, the bulk of the rain falling in a 48-h period and maximum ranfall rates attaining values in exceedence of 110 mm/h.

† q (Nm^{-1}) = $½\rho V_h^2 = ½\rho[(h/h_r)^k]^2$; V_h , wind speed, height h, V_r , reference wind speed, k = 1/7 for open flat terrain; k = 0.5 for urban terrain; ρ: ρ_{air} (0°C) = 1.293 kgm^{-3}

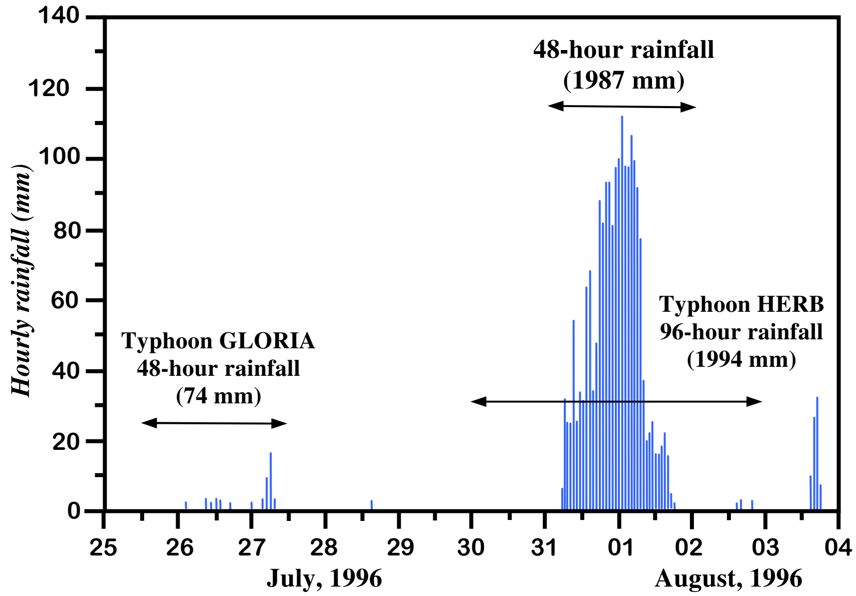

FIGURE 2: TEMPORAL RAINFALL; TYPHOON GLORIA AND HERB, TAIWAN 1996, ADAPTED FROM [24]

Values of wind-driven rain for selected Canadian cities

A summary of extreme wind-driven rain (WDR) conditions in relation to the return period in years for different locations across Canada is given in Table 4 and includes: Sandspit, BC, Calgary, AB, Toronto, ON, Ottawa, ON, and St. John's, NL [25].Information on rates of wind driven rain (L/hr-m^2) and driving rain wind pressures (DRWP) are given as average hourly values. The DRWP is the velocity pressure exerted on a surface (e.g. wall) normal to the wind direction during rain. Sandspit, BC is located on the north eastern tip of Moresby Island (part of the Queen Charlotte Islands) and is thus in a moist coastal climate. St. John's is likewise located in a moist coastal climate receiving 1200 mm of rainfall annually as compared to 1300 mm in Sandspit.

With reference to a 1 in 30 year return period, of the five selected locations, the most significant WDR conditions occur in Sandspit (WDR, 0.97 L/hr-m^2; DRWP, 630 Pa) whereas Toronto has a much-reduced WDR load of about half the rain deposition and a third the driving pressure (i.e. WDR, 0.50 L/hr-m^2; DRWP, 225 Pa). The values provided for Ottawa are comparable to those of Toronto and interestingly in Calgary, in respect to WDR, loads are at least as significant as those of Ottawa or Toronto, whereas the DRWPs are greater (WDR, 0.625 L/hr-m^2; DRWP, 347 Pa). This is likewise evident for return periods of 1 in 2, 1 in 5 and 1 in 10 years. Given the higher DRWPs in Calgary, this suggests a heightened risk to water entry in Calgary as compared to either Ottawa or Toronto. The WDR loads in St. John's are comparatively high in relation to all other locations with the exception of Sandspit; this is to be expected given its coastal location.

TABLE 4: SUMMARY OF HOURLY DRIVING RAIN WIND PRESSURES AND WATER DEPOSITION RATES FOR A SELECT SERIES OF CANADIAN CITIES AND RETURN PERIODS [25]

Location	**SAN**		**CAl**		**TOR**		**OTT**		**STJ**	
Return Period (yr)	WDR, L/hr-m^2	DRWP, Pa	WDR, L/hr-m^2	DRWP, Pa	WDR, L/hr-m^2	DRWP, Pa	WDR, L/hr-m^2	DRWP, Pa	WDR, L/hr-m^2	DRWP, Pa
2	0.35	431	0.25	157	0.25	106	0.27	116	0.46	286
5	0.63	505	0.42	230	0.36	151	0.45	158	0.64	400
10	0.76	553	0.50	277	0.42	180	0.53	186	0.74	476
39	0.97	630	0.625	347	0.50	225	0.67	228	0.87	595

SAN = Sandspit, BC; CAL = Calgary, AB; TOR = Toronto, ON; OTT = Ottawa, ON; STJ = St. John's, NL

OVERVIEW OF A RECENT STUDY TO ASSESS VULNERABILITY OF MODEL JOINTS TO EXTREME CLIMATE LOADS

The fault tolerance of simulated vertical and horizontal panel joints was assessed in a laboratory study [26] in which the degree of watertightness of defective joints was determined by subjecting the joints to a range of simulated wind-driven rain loads, loads that were consistent with those that might be found atop tall buildings in a severe storm event. The watertightness tests were carried out using a purposely developed test apparatus shown in Figure 3a. Using this apparatus the basic wind-driven rain parameters at a panel joint could be replicated (i.e. rain deposition, pressure differential) and the conditions at the joint were thus simulated in a reproducible manner.

The configuration of the vertical joint is illustrated in Figure 3b; as is evident, the vertical joint was located at the middle of the specimen, the overall size of which was 610-mm by 610-mm. The joints were 20 mm wide (15 mm depth) and consisted of a one-component polyurethane product and closed cell backer rod (25 mm diam.). Small deficiencies (cracks), ranging in size between 2 and 16 mm in length, were purposely introduced in the jointing product (Figure 4a) at approximately mid-length of the joint, thus permitting water to pass through these openings. One portion of the panel assembly was fixed to the test frame the other was moveable thus permitting the width of the joint to be changed up to a maximum of approximately 10% the 20 mm joint width (i.e. ca. 2 mm). The joint displacement also changed the nature and size of the crack. As a result, joints with cracks of varying length and size were subjected to water spray rates ranging between 1.6 and 6 $Lmin^{-1}m^{-2}$ and pressures of up to 2 kPa. An outline of the water penetration test matrix on the vertical joints is given in Table 5. The panel assembly, and substrate to which the sealant was applied, was made of transparent acrylic sheathing (Figure 4b); this permitted visual observation of water penetration along the joint in different test conditions over the course of the investigation. Water penetration tests were carried out over a period of ten minutes for each test parameter. A select set of results are provided in Figure 5 [27]; these provide rates of water leakage across the vertical joint in relation to the pressure difference and water deposition rate for joints having 10% displacement (2 mm) and crack lengths varying between 2 and 16 mm.

TABLE 5: TEST MATRIX FOR WATER PENETRATION TESTS ON VERTICAL JOINTS [27]

Crack length (mm)	Joint displacement (mm)	Quantity of water L/(min-m^2)			
		1.6	3.4	4	6
No crack (0)	0, 0.5, 1, 2	-	-	-	6*
2	0, 0.5, 1, 2	6*	1**	6*	6*
4	0, 0.5, 1, 2	-	1**	6*	-
8	0, 0.5, 1, 2	-	1**	6*	-
16	0, 0.5, 1, 2	6*	1**	6*	6*

*6 tests at : 0, 75, 150, 500, 1000, 2000 Pa, **1 test at : 150 Pa

These results in general indicate that the rate of water leakage increases at higher water deposition rates on the specimen or air pressure differential across the specimen. As well, it shows that rates of leakage, as might be expected, increase with crack size, as determined by the length of the crack and the displacement of the joint. Essentially, the larger the opening through which water can flow, the greater the potential for water entry; this of course is well understood however, this information provides some measure of the magnitude of the effects of such deficiencies atop buildings. Specifically, at a pressure difference of 200 Pa, rates of entry may vary from lower values of 5 mL/min upwards to 12 mL/min with rates achieving 24 mL/min at 1000 Pa. These are not insignificant amounts of water considering the length and frequency of rain events and the likely cumulative number of deficiencies along any one joint.

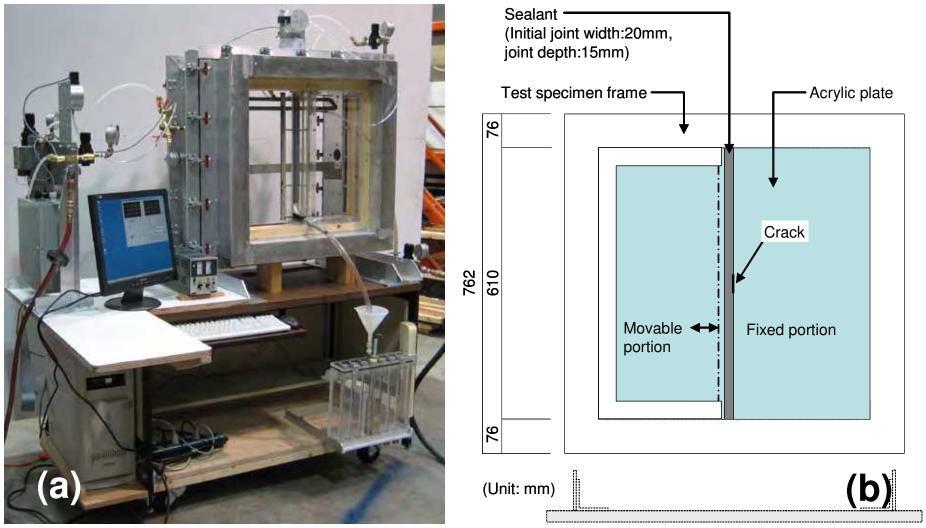

FIGURE 3: (a) MINI-DYNAMIC WALL TESTING FACILITY CONFIGURED FOR TESTING VERTICAL JOINT; (b) FRONT ELEVATION OF TEST SPECIMEN SHOWING 20-MM VERTICAL JOINT AND NOMINAL DEGREE OF MOVEMENT OF TRANSPARENT ACRYLIC PANEL

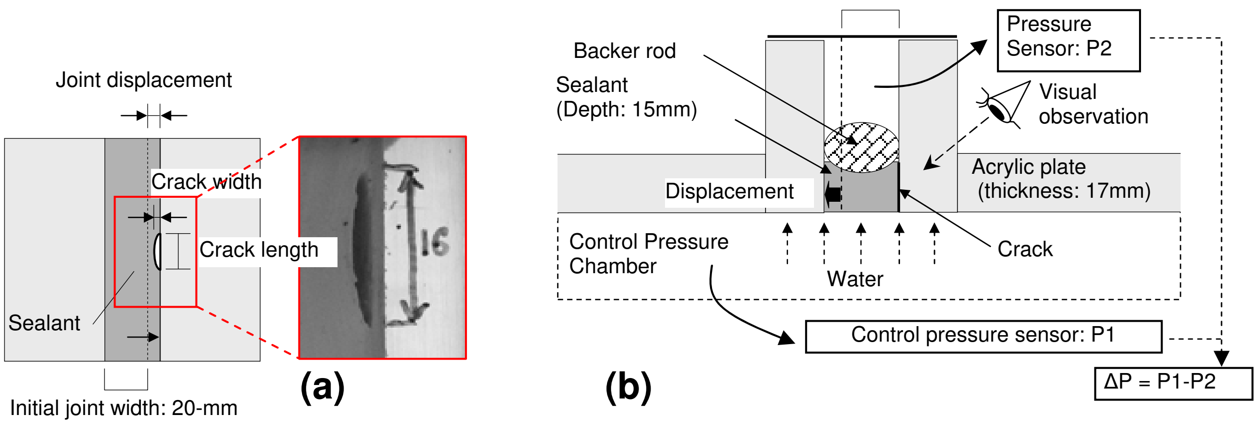

FIGURE 4: (a) SEALED JOINT SHOWING CRACK LENGTH AND WIDTH, JOINT DISPLACEMENT; (b) METHOD OF TESTING SHOWING JOINT CONFIGURATION (SEALANT AND BACKER ROD) ACRYLIC PLATE ASSEMBLY, DIRECTION OF DISPLACEMENT AND LOCATION OF CRACK [27]

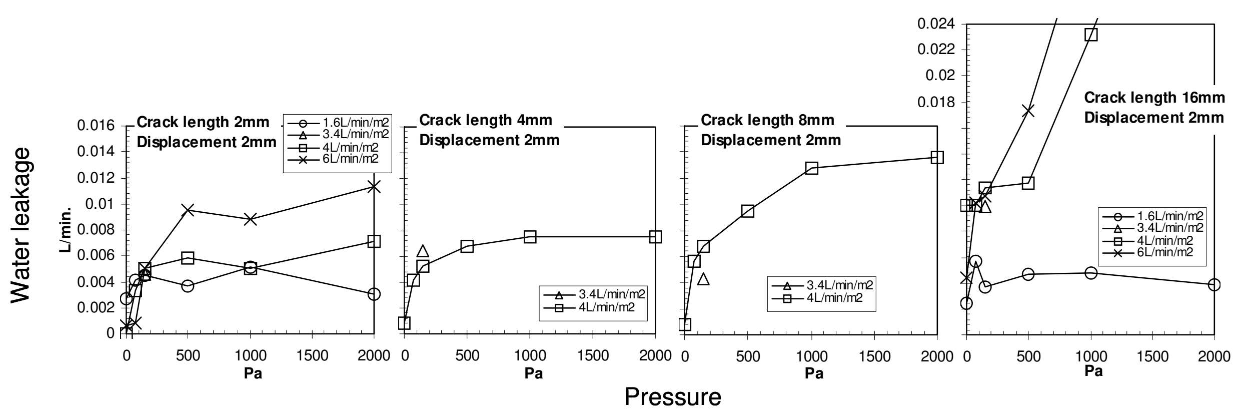

FIGURE 5: SELECTED RESULTS FROM WATER PENETRATION TESTS; WATER LEAKAGE ACROSS JOINT (L/MIN) GIVEN IN RELATION TO PRESSURE DIFFERENCE (PA) AND WATER DEPOSITION RATE (L/MIN-M^2) FOR JOINTS OF 10% DISPLACEMENT (2 MM) AND CRACK LENGTHS VARYING BETWEEN 2 AND 16 MM [27]

Hence atop buildings where wind-driven rain loads are most severe, joints are perhaps most vulnerable, although the downward migration of water along vertical pathways also poses a risk to any deficient joints further down on the facade. This information coupled with some basic notions on the vulnerability of southerly exposed joints of buildings, offers some insights into where problems regarding joints may occur. In respect to the maintenance of buildings and the inspection of joints, this information may provide a better appreciation of which joints are most vulnerable and where inspection should first proceed.

CONCLUSIONS AND RECOMMENDATIONS

The fault tolerance of jointing systems has been reviewed on the basis of understanding the deterioration of jointing products in general and thereby determining the more vulnerable locations on buildings. This when related to appreciating the magnitude of wind-driven rain loads on buildings provides a means of coupling the significance of deficient joints to wind driven rain and thus the likelihood to water entry at these joints. An example is provided of a laboratory study conducted to establish the amount of water entry for deficient joints when subjected to simulated wind-driven rain loads as might be found atop a high-rise building located on the coast; results show the dependence of water entry on pressure difference and water deposition over the openings and the size of cracks in deficiency joints; significant amounts of water can accrue over short periods of time.

The information provided here is relevant to the maintenance management of façade jointing systems and the inspection of joints as information is provided on the location of the most vulnerable joints and the type of joints most likely to become deficient over the life of the building. However, there are several tasks that have yet to be realized. For example, there remains developing a model for distribution of sealant failure on buildings based on inspection results; a model to relate sealant failure to overall building joint system performance; a model to relate loss in performance with maintenance actions and thereafter to maintenance and refurbishment costs. To date a framework has been devised that permits integrating such models to the overall facade maintenance management approach as proposed by Kyle in [3]. A means of aggregating performance data has already been established thus basic methods that permit relating performance to costs have been developed and can be used in the same manner for jointing systems.

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